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Life-Cycle Assessment of coal–biomass based electricity in Chile: Focus on using raw vs torrefied wood

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ABSTRACT

In this article, the environmental impacts associated to cofiring coal with forest biomass for electricity production in Chile are analyzed for: (i) untreated pine pellets and (ii) torrefied-pretreated pine pellets. Results show that energy production from cofiring coal/untreated wood pellets or coal/torrefied pellets, featured significant reductions in environmental impacts, as compared with pure coal plants. Indeed, reductions in acidification (28–26%), abiotic depletion (15–7%), eutrophication potential (15–12%), global warming potential (16–6%), photochemical oxidation (28–23%), human toxicity (17–15%), terrestrial ecotoxicity (12–9%), and marine aquatic ecotoxicity (17–15%) were obtained when untreated or treated pellets were used as a substitute for coal. Moreover, the environmental profile of torrefied pine evidenced its low impact per energy unit, in most of the studied categories except for eutrophication and marine aquatic ecotoxicity, for which the harvesting, logistic chain and torrefaction processes were the most important contributors.

Introduction

Energy security concerns, excessive fossil fuel consumption, increasing pollutant emissions and incipient and worrisome climate change are the main drivers for more aggressive development of renewable energy sources. In this framework, forest biomass is a potential candidate to replace fossil fuels from their current applications, based on its abundance, renewability, carbon neutrality, and the possibility of conversion to higher-value-added products. Forest biomass is near neutral in CO_2, as some authors argued that the growing trees absorb the CO_2 emitted during combustion creating a closed carbon loop (Bracmort, 2013). Nevertheless, it has also been demonstrated that the quantity and composition of greenhouse gasses (GHG) produced in biomass-based power generation systems depends upon the type of feedstock and the way it is burned (Weisser, 2007; Royo et al., 2012). Accordingly, the introduction of such resource into traditional energy matrices should be done from the sustainable perspective by integrating technical and environmental principles.

Chile has experienced a fast economic growth in the last decades featuring an average increase in energy demand around 94 PJ/y between 2009 and 2013 (MinEnergía, 2014). Electricity production in Chile heavily relies on imported fossil fuels, with coal-fired power plants accounting for about a third of total installed capacity (viz. 3541 MW in Sept. 2015), driven by low natural gas and coal prices. This framework resulted from an economic-based decision procedure, supported by the low prices of natural gas and coal. Nevertheless, it has been envisaged that such dependence on volatile international energy prices represents a threat to the country's stability (MinEnergía, 2013), hence actions should be taken to change the *status quo* by considering national resources.

With more than 15 million hectares of native and forest plantations and a yield of 20–40 m^3/ha/y, Chile has one of the largest and productive forested areas in Latin America (Berg et al., 2013; CONAF, 2014). Forest management and processing, generates approximately 4 million of tonnes/year of woody residues which is equivalent to 14,000 GWh/y of energy, enough to replace an important fraction (viz. 25%) of the internal coal demand (Berg et al., 2013). Currently, the installed capacity for electricity production from biomass amounts to nearly 5% of its estimated potential, and these are mostly designed to meet internal energy demand in paper and wood industries (Martínez-Saperas, 2014). Therefore, there is an interesting opportunity to transform the local energy matrix into a more sustainable one.

Among several options, integrating forest biomass to coal-fired power plants is an attractive option to revamp current installations. Indeed, this alternative offers a number of advantages, such as lower

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investment risks, greater efficiency, low costs and easiness to implement. As a result, the number of traditional coal fired boilers turned into biomass co-firing plants around the world has increased, from 152 to 241 in only 5 years (Al-Mansour and Zuwala, 2010; IEABCC, 2012). Most common practice is to develop the combustion of coal and biomass in air-fluidized bed reactors, where particles are suspended in a bed of ash, sand or limestone (Oka and Anthony, 2004). Cofiring with biomass usually occurs at temperatures between 800 and 1000 °C; with maximum up to 1400 °C, when the process is carried out in pulverized-coal boilers, but the feeding of untreated biomass in these systems is rather complex and impractical (Kalisz et al., 2008). According to Baxter (2005), cofiring ranked as the best option for countries that are looking for ways to reduce global warming, because it brings environmental benefits such as reduction of CO_2, SO_2 and also NO_x for some biomass types. Nevertheless, such transformation is not a straightforward process and it has both, technical and environmental burdens. Biomass features a number of technical constraints as compared with solid fossil fuels, such as higher biodegradability, higher moisture content, lower energy density, discrete distribution, lower grindability and hydrophilic (Almeida et al., 2010). On the other hand, main environmental concerns are related to land use, transport and distribution chains and, on ensuring a long-term availability of biomass with the required quality at a competitive cost (Cambero and Sowlati, 2014). Pretreatment of bio-resources by physical, biological or thermochemical methods, may help to mitigate problems associated to variable fuel quality. Furthermore, if the treatment leads to the increment of the energy density, the cost and environmental impacts per energy unit of transported fuel may decrease. In this respect, torrefaction is an emerging thermal biomass pretreatment method that has the ability to reduce biomass heterogeneity, increase its energy density and reduce hygroscopic behavior, and fibrous nature. This process is defined as mild pyrolysis and takes place between 200 and 320 °C (Bergman, 2005; Chew and Doshi, 2011; Batidzirai et al., 2013; Nhuchhen et al., 2014). Throughout torrefaction, the tenacious fiber structure of the original biomass is largely destroyed through the breakdown of hemicellulose and, to a lesser degree, cellulose and lignin molecules, so that the material becomes brittle and easier to grind (Phanphanich and Mani, 2011). With the removal of oxygen-rich lighter volatile fraction, the highest heating value (HHV) of the remaining material gradually increases at expenses of a mass reduction, retaining around 90% of its initial HHV. Key torrefaction reaction products include solids in the form of char, ash and volatiles (gasses and organic vapors) (Prins et al., 2006; Bates and Ghoniem, 2012; Kiel et al., 2012). Technical studies have shown that 20% of coal could be substituted by torrefied biomass, without the need for further significant investments, thus contributing to a reduction in fossil carbon emissions (Lempp, 2013).

Although cofiring biomass (untreated or torrefied) could be a more sustainable way to produce energy from wood in existing facilities, there are still some environmental concerns that need to be evaluated, such as emissions profiles, global warming potential, acidification, ozone depletion, eutrophication, ecotoxicity, etc. along the whole biofuel life cycle.

Life Cycle Assessment (LCA) is a stepwise methodology to evaluate impacts associated to a product, technology or stage in a process. LCA includes the attributes or aspects of the natural environment, human health and resources associated to a product's life from raw material acquisition to processing, manufacturing, use and, finally, disposal (ISO 14044, 2006). There are several reports on the application of LCA to analyze the cofiring of woody biomass (Table 1) in Europe and Asia, and references of such analysis in Latin America and especially in Chile are scarce.

Works in Table 1 vary in detail and scope but all of them concluded that each case should be analyzed individually, because site specific regional, demographical and economic characteristics influence the environmental performance and impacts of technologies.

Most LCA studies on torrefaction, mainly focus on its integration to cofiring for electricity generation and, there is still a knowledge gap on the environmental comparison between torrefied biosolid and coal (Al-Mansour and Zuwala, 2010; Tabata et al., 2011; Huang et al., 2013; Tsalidis et al., 2014). This study addresses this issue for the Chilean case, presenting the environmental profile of torrefied biomass for its future application in different systems such as electricity generation, cement industry, gasification and integrated gasification–Fischer Tropsch systems. Additionally, the use of torrefied biomass as blend fuel for electricity generation in coal-fired thermal plants is also presented.

Pinewood (*Pinus radiata*) is used here as the biomass feedstock, since this species accounts for more than 60% of forest plantations in the country (CONAF, 2014). Most inventory data for torrefaction and cofiring plants were obtained in pilot-scale experiments, whereas complementary upstream and downstream data were acquired using Ecoinvent database and sequential modeling (Arteaga-Pérez et al., 2015). Experimental results for cofiring were extrapolated to a 250 MWe plant, considering a negligible effect of coal substitution (up to 20%) on energy efficiency, temperature profiles and flue gas composition.

Methods

The SimaPro v8.0.2 and CML2 baseline 2000 v2.05, world 1995 model were used in this study. The CML2 was originally developed by the “Centre for Environmental Studies (CML)” at the University of Leiden, the Netherlands, in 1992. The impact categories included in this method are: abiotic depletion (ADP), acidification (AP), eutrophication (EP), global warming (GWP), ozone layer depletion (ODP), human toxicity (HTP), fresh water ecotoxicity (FAETP), marine aquatic ecotoxicity (MAETP), terrestrial ecotoxicity (TETP) and photochemical oxidation (POCP).

LCA methodology

The LCA methodology is thoroughly described elsewhere (Guinée, 2001). Here, a brief summary of the main LCA stages is presented below

Goal and scope definition

The aim of this LCA is to compare alternative processes for power production using woody biomass as fuel substitute in coal-fired power stations. Two scenarios are analyzed using a cradle-to-gate approach: (i) cofiring of coal with 20% (energy basis) of untreated wood pellets and (ii) cofiring of torrefied wood pellets with coal under the same replacement ratio. Both cases are compared with installed coal-fired power stations in Chile, based on all impact categories included in the CML baseline 2000 model. The choice of both scenarios is in line with Chilean government decision to substitute 10% of fossil-based electricity production by renewables by 2024 (MinEnergía, 2013). As mentioned above, cofiring is a simple and low cost alternative to take advantage of forest residues as fuels for electricity production in Chile. Moreover, torrefaction is a very promising process to increase quality, compatibility and competitiveness of forest resources in comparison to coal. Accordingly, the environmental profile of non-pelletized torrefied material is studied and compared with that of coal.

System boundaries

The cradle-to-gate boundaries of coal and biomass for power generation in thermal stations are shown in Fig. 1.

The biomass chain included production, harvesting, transportation, pelletization, cofiring and electricity generation. In the case of pretreated biomass, boundaries are extended (dashed lines area) to the torrefaction plant. *P. radiata* was used as reference to estimate the impacts of forestry production process, which included plantation establishment, management, harvesting and transportation. Transport of pesticides and fertilizers was not considered here, since preliminary estimations showed that associated environmental burdens were

Table 1
Summary of reference on LCA of biomass-coal cofiring applications.

Reference	Biomass	Criteria	Region	Torrefaction
Benetto et al. (2004)	- Coppices - Wet sawdust	GHG	Europe (France)	NO
Huang et al. (2013)	- Rice straw	IMPACT 2002 +	Asia (Taiwan)	YES
Jenjariyakosoln et al. (2014)	- Sugarcane residues	GHG	Asia (Thailand)	NO
Perilhon et al. (2012)	- Wood waste	IMPACT 2002 +	Europe (France)	NO
Royo et al. (2012)	- Harvested (crops and forest)	GHG	Europe (Spain)	NO
Schakel et al. (2014)	- Wood - Straw	ReCiPe	North western Europe	NO
Sebastián et al. (2011)	- Harvested (crops and forest)	GHG	Europe (Spain)	NO
Tabata et al. (2011)	- Woody biomass	GHG	Asia (Japan)	YES
Thakur et al. (2014)	- Forest residues	GHG	America (Canada)	NO
Tsalidis et al. (2014)	- Woody biomass	CML/Traci	Europe (Netherlands)	YES
Zuwała (2012)	- Willow chips - Residual wood	Eco-indicator 99	Europe (Poland)	NO

negligible as compared with biomass transport. Furthermore, the production of natural gas, diesel (transport fuel) and fertilizers was considered by using the data available in Ecoinvent database. Boundaries for coal chain included production and transportation to Chilean harbors. Since all Chilean coal power plants are located near port facilities, coal transport from Chilean ports to power plants was neglected here.

Functional unit

Two functional units were used:

(i) One MJ of energy contained in the fuel, was used to compare the environmental profiles of coal and non-pelletized torrefied biomass. The estimation of the energy content was done on the basis of typical fuels heating values in Chile, viz 26 MJ/kg and 21.6 MJ/kg, for coal and torrefied wood respectively
(ii) One kWh of electricity at the power plant gate to compare the environmental impacts of cofiring untreated and torrefied pine pellets for electricity generation in the traditional coal-fired power plants.

Cases location and other assumptions

The LCA assumes that all biomass is produced, pretreated and used within the Biobío Region (VIII Region), Southern Chile, where more than 50% forest plantations are located (CONAF, 2014). A set of process data for torrefaction was obtained from a hybrid experimental-modeling approach, because up to date there are no commercial installations in operation. Pilot-scale experiments for cofiring conducted at the Technology Development Unit at the University of Concepcion were used to linearly scale up the emissions and resources for a 250 MW plant. It must be mentioned that reactor temperature profiles, thermal efficiency and composition of flue gasses and ash, obtained from pilot scale experiments were quite similar to those found under similar operating conditions in real full-scale plants (Garcia and Flores, 2012). Furthermore, it was assumed that up to 20% of coal substitution by biomass pellets, either raw or torrefied, would not have a significant effect on combustion efficiency. Even when previous reports (Cremers, 2009; Lempp, 2013) suggest that, this substitution could reach up to 50% (energy based), investment required above 20% substitution setup significantly. Specific details on pilot plants and operational estimations are given below.

Processes data

Primary data for pinewood cultivation, harvesting and transportation was used here. Moreover, material flowrates, and emission compositions in biomass torrefaction, pelletization and cofiring were assessed based on pilot-plant experimental results. Pre-drying and volatiles recirculation impacts were included in torrefaction inventories. Mass balances complemented with simulations with AspenOne v.8.6 software (Aspen Technology I, 2014) were used to complete the necessary process information. All assumptions and data used to carry out the process

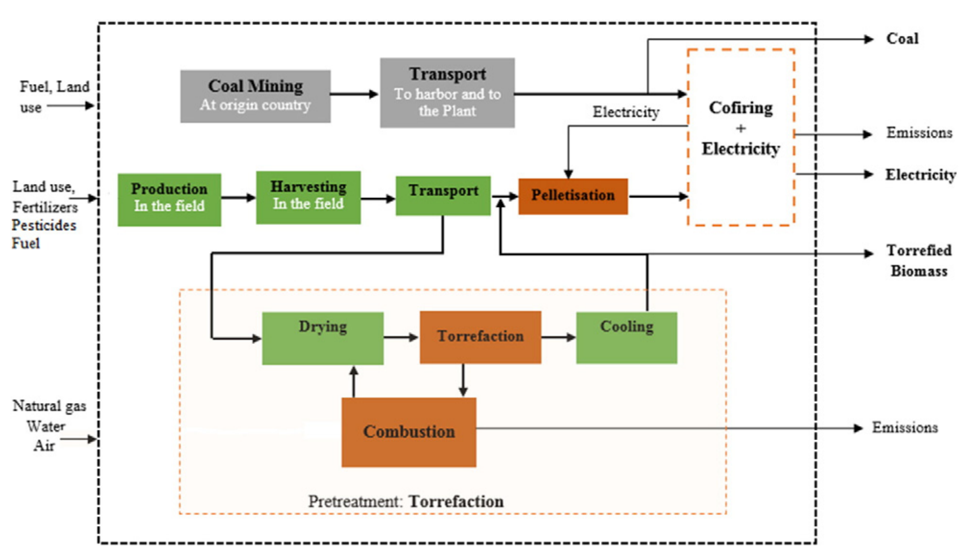

Fig. 1. System boundaries.

inventories are described below. A detailed torrefaction modeling description could be found in a previously published paper (Arteaga-Pérez et al., 2015).

Coal

Data on the coal supply chain was obtained from a previous work conducted by the authors Fondef D06I1060 (Vega and Zaror, 2011a,b), where a complete database for the Life Cycle Inventory of Chilean electricity production and distribution within the period 1995–2011 is presented. The database was prepared using primary data on fuel consumption, generation infrastructure, installed capacity, efficiencies per technologies and changes in the electric matrix on a yearly basis. Currently, the coal used in Chile is mainly imported and extracted from coal mines in Colombia (80%), North America (14%), and Australia (6%), and then transported by transoceanic freight ships to Chilean harbors. As special feature, most of the thermal plants in Chile are located near to the harbors. Specific data for transport was gathered form Ecoinvent database.

Wood cultivation, harvesting and transportation

It is recognized that wood cultivation and harvesting are key forestry processes featuring significant environmental burdens. Table 2 below summarizes the main forestry process data used in this study. In Chile, feedstock for industrial wood processing and firewood is generated in wood plantations. *Eucalyptus globulus* and *P. radiata* are dominant species in Chilean wood plantations; the former is mostly used as raw material for pulp production, whereas the latter is used as a raw material for a wider range of applications. *P. radiata* plantations represent more than 60% of total planted surface, featuring an average annual growth of more than 15 m^3/ha (INFOR, 2014), and is used as the only source of firewood in the present study.

Cultivation and harvesting. For pine cultivation, the intensive management scenario described by Rubilar (2005) was considered here. This process includes land preparation, weed control, fertilization, mechanical seedling, plantation management, and harvesting after 18–25 year growth. Afterwards, a new plantation cycle begins. Glyphosate and atrazine are the main herbicides used in forestry applications, whereas nitrogen, potassium and boron are considered critical fertilizers at the time of plantation establishment. Herbicides and fertilizer loads used in this study are shown in Table 2. Special machinery used during forestry operations includes tractors, harvesters, forwarders and skidders, involving diesel and lubricants consumptions, as well as combustion gasses emissions.

The amounts of diesel consumed in the cutting and other field operations were obtained from primary data (Vega and Zaror, 2011a,b). Air emissions from fuel combustion were calculated based on specific emission factors associated to the machinery used for field operations, which are reported in Ecoinvent database.

Wood transportation. This stage was analyzed considering wood haulage to the pretreatment plants (torrefaction/pelletization) and further transportation of woody fuel to the power plant, using truck lorry (16–32 t). Limits for wood hauling were estimated at an average of 150 km round truck trip, based on the locations of the forest plantations, chipping station, torrefaction and power generation plants (see Fig. 2). The use of biomass in such a small catchment area may introduce benefits associated to costs and to the reduction of carbon footprint. This is in fact, one of the major reasons for using woody biomass as energy source in the Biobío region. Inventory transportation data was obtained from Ecoinvent database whereas, distances for transport were calculated from Google earth based on the information gathered from forest industry statistics, reported by Chilean Forest Institute (INFOR) (INFOR, 2014).

Table 2
Process data for agricultural stage.

Resources for operations	Unit	Value	Ref.
Pine wood basic density	kg/m^3	450	Dias and Arroja (2012)
Pine wood moisture content	% dry basis	40	
Herbicide for soil preparation	kg (glysophate)/ha	1.6	Rubilar (2005)
Herbicide for weed control	kg (glysophate)/ha	2.0	Rubilar (2005)
Herbicide for weed control	kg (anthracine)/ha	3.0	Rubilar (2005)
Fertilizer (triple superphosphate)	kg P_2O_5/ha	80	Rubilar (2005)
Inputs from environment			
Use of land (seeding)	ha/y	26.8	Rubilar (2005)
Use of water (seeding)	m^3/ha	0.216	Morales et al. (2015)
Inputs from technosphere			
Pinus radiata seeds	kg/ha	2.5	González-García et al. (2014)
Fertilizer			
N-based fertilizer[a]	kg/ha	12	Rubilar et al. (2008)
Triple superphosphate[b]	kg/ha	120	Rubilar et al. (2008)
Pesticides	kg/ha		Rubilar (2005)
Glyphosate	kg/ha	2	Rubilar (2005)
Atrazine	kg/ha	3	Rubilar (2005)
Fuel use	kg/ha	1500	
Outputs to technosphere			
Pinewood yield	m^3/ha	446.5	Vega and Zaror (2011a,b)
Outputs to environment			
Emission to air			
N_2O	kg/ha	0.036	EPA (1998), CONAMA (2009)
NH_3	kg/ha	0.36	EPA (1998), CONAMA (2009)
SO_2	kg/ha	1.94	CONAMA (2009)
Emission to water			
Total P	kg/ha	0.22	Dias and Arroja (2012)
NO^{3-}	kg/ha	1.08	IPCC (2006)

[a] 30% N.
[b] 42% P_2O_5.

Fig. 2. Plants and forest locations (VIII Region Biobío).

Output from forestry processes. The outputs considered for forestry operations include air emissions from fuel combustion and air and water emissions from fertilizer applications. Combustion emissions derived from diesel combustion in agricultural and forest machineries (tractors, harvesters, forwarders and skidders) were taken into account using specific emission factors from Ecoinvent. Application of N-containing fertilizers was considered to release N_2O and NH_3 to the atmosphere and nitrates NO_3 to water. Emission factors of 0.01 kg N_2O–N, 0.1 kg NH_3–N and 0.3 kg NO_3–N per kg of N in fertilizer were adopted. Application of P-containing fertilizers in pine stands was considered to release P to water. As suggested by Audsley (2003), an emission factor of 0.024 kg P per kg of P in fertilizer was considered. The use of triple superphosphate as mineral fertilizer involved phosphate emissions into water. This emission was estimated according to the emission rate used by González-García et al. (2014): 0.01 kg/kg of applied P.

Torrefaction process data

A pilot-scale torrefaction plant is installed at the Technology Development Unit (UDT) at the University of Concepcion. This plant has a capacity of 100 kg/h and it was designed to operate between 250–300 °C, at atmospheric pressure and 15–30 min residence time (Fig. 3).

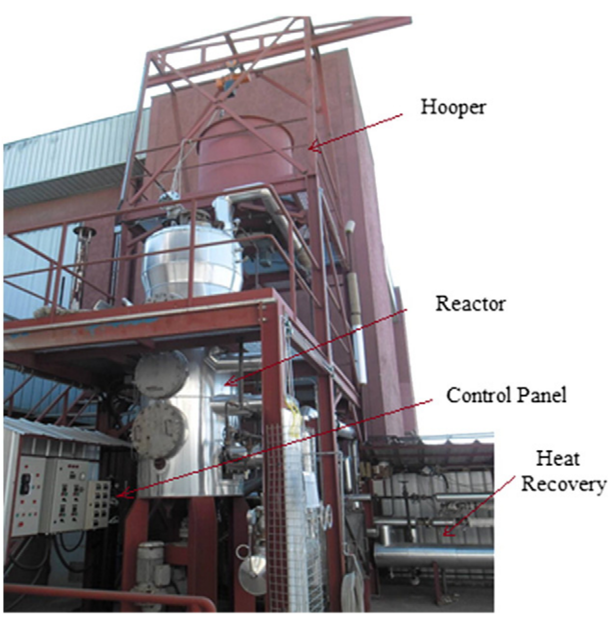

Fig. 3. Torrefaction plant installed at UDT (University of Concepción).

Biomass drying is the most energy-intensive stage in the torrefaction process (Basu, 2013; Arteaga-Pérez et al., 2015), hence this stage was included in the inventory due to its significant effect on resource consumption. Therefore, pine pretreatment involved four stages: drying, torrefaction, steam generation and cooling of torrefied products. Drying was modeled according to equations proposed by Basu (2013) and Zakri et al. (2013), using an Aspen One v8.6 simulation model reported in a previous paper (Arteaga-Pérez et al., 2015). Emission of organic vapors was avoided by recirculating volatiles to supply the required energy for drying and torrefaction. The heat needs that were not fulfilled by burning volatiles, were produced through natural gas at a combustion efficiency of 90%. In Table 3, processing data and product characterization are presented.

Cofiring process data

This analysis was based on the actual Chilean schemes for electricity production from coal, and it included the following options: (i) coal fired plants, (ii) cofiring coal/untreated pine pellets and (ii) cofiring coal/torrefied pine pellets. The net electrical efficiency was set at 30% according to data facilitated from local thermoelectric companies (Vega and Zaror, 2011a,b). Cofiring experiments were developed in a pilot plant installed at UDT, comprising a fluidized bed with 50 kg/h (average power 250 kWth) capacity, systems for solid separation (cyclones) and flue gas composition measurements (EKOM model J2KN PRO) (Fig. 4).

The plant was operated at 850 °C and atmospheric pressure for coal combustion and using of 80/20 coal/pine mixtures (energy based). The experimental data used in the inventory were reactor temperature, flue gasses composition (NO_x, SO_x and CO_x) and temperature, airflow and temperature, coal and biomass composition and mass flowrates and conversion efficiency. A summary on process data is provided in Table 4.

Table 3
Torrefaction process data.

Torrefaction process data		Biomass composition		
Torrefaction temperature (°C)	280	*Ultimate analysis*	*Untreated*	*Torrefied*
Reactor residence time (min)	30	Carbon (%)	48.94	53.66
Results/requirements		Hydrogen (%)	6.91	6.33
[a]Solid yield (%)	65	Nitrogen (%)	0.12	0.16
[a]Volatile yield (%)	35	Sulfur (%)	0	0
Electricity use (kWh/kg)	0.05	Oxygen (%)	43.73	39.54
Steam requirement (kg/kg)	1.01	Ash (%)	0.30	0.30
Fuel requirements (MJ/kg)	1.3	HHV (MJ/kg)	18.89	21.60

[a] Yields are defined in dry ash-free basis as reported in Arteaga-Pérez et al. (2015).

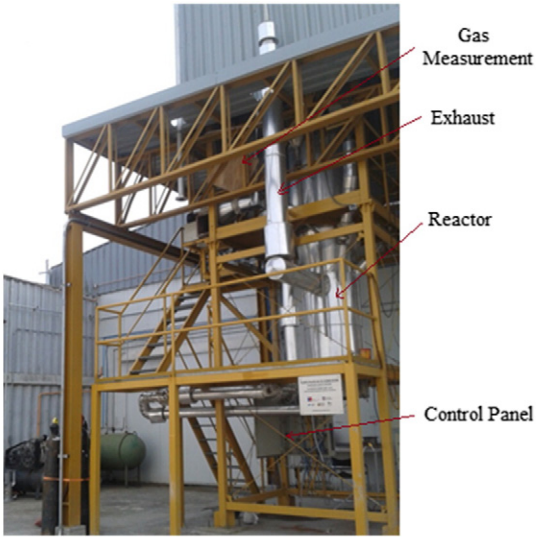

Fig. 4. Cofiring plant installed at UDT (University of Concepción).

Data summarized in Tables 2, 3 and 4 are used – along with Ecoinvent database – for estimating the LCA and LCI of the processes under consideration.

Results and discussion

Inventory data

The Life Cycle Inventory data used for comparing coal with torrefied wood and for the two cofiring cases (coal/raw pellets and coal/torrefied pellets) are presented in Tables 5 and 6.

Environmental profiles of torrefied biomass and coal

Impacts associated with the production of two different fuels: coal and torrefied biomass, were compared using the categories of CML 2000. The environmental profile of torrefied wood is listed in Table 7, where each category is given in impact points per 1 MJ of energy contained in the fuel.

Results shown in Table 7 and Fig. 5 are independent on the final application of these fuels, allowing a basis for comprehensive comparison of prospective options. These results do not include the pelletization process.

As shown in Table 7 and Fig. 5, most of the impact categories for torrefied wood presented lower impact characterization values, except for eutrophication, human toxicity and marine aquatic ecotoxicity. A detailed discussion on each category is provided below.

When compared to coal, *Abiotic depletion* decreased about 11% for torrefied wood. The main reason for such a high ADP for coal is due to the mining (95%) processes and the long distances for transportation. In the case of biomass, torrefaction process increased the non-renewable load due to the usage of natural gas for steam production, which is traduced in a contribution of 84% to the ADP (Fig. 6). This behavior may change if the steam is produced using biomass instead natural gas, as fuel for the boiler.

Acidification potential is a response to the emissions of acid gasses such as SO_2, NH_3, and nitrogen oxides. This category is lower for torrefied biomass (20%). Major effects in both coal and torrefied wood, may be attributed to the SO_2 emissions during transport with a net contribution of 65% and 67% respectively.

Global warming potential for torrefied wood was considerably lower than that of coal. The reuse of volatiles to supply the process heat could

Table 4
Cofiring process data.

Parameter	Coal/raw pellets	Coal/torrefied pellets
Coal substitution (kgB/kg coal)	0.275	0.24
Electricity (kWh/kgB)	9	12
Waste heat (kWh/kgB)	33	34
O_2 (kg/kgB)	1.06	1.07
$CO_{2\ fossil}$ (kg/kgB)	6.1	4.5
$CO_{2\ Biogenic}$ (kg/kgB)	1.12	1.29
NO_x (kg/kgB)	0.17	0.15
SO_2 (kg/kgB)	0.096	0.079
Ash (kg/kgB)	3.2	0.71

Note: kgB refers to kg of biomass pellets entering the cofiring plant.

Table 5
Life cycle inventory data. Coal and torrefied wood (*P. radiata*). Functional unit 1 MJ.

	Units	Coal	Torrefied wood
Atmospheric emissions			
CO_2 fossil	kg/MJ	6.50E−02	4.03E−03
CO_2 biogenic	kg/MJ	1.04E−04	3.65E−05
N_2O	kg/MJ	8.90E−07	4.17E−07
CO fossil	kg/MJ	6.18E−05	1.70E−05
NO_x	kg/MJ	1.39E−04	7.88E−05
SO_2	kg/MJ	4.27E−05	3.93E−05
CH_4 fossil	kg/MJ	2.23E−03	2.81E−05
PM 10	kg/MJ	1.32E−05	3.92E−06
PM 2.5	kg/MJ	8.63E−06	2.39E−06
Discharges to water			
BDO_5	kg/MJ	5.16E−05	1.29E−05
COD	kg/MJ	5.58E−05	1.34E−05
Sulfate	kg/MJ	4.19E−04	2.92E−03
Nitrate	kg/MJ	3.06E−06	3.79E−05
Phosphate	kg/MJ	1.46E−05	1.26E−04
Natural resources			
Crude oil	kg/MJ	4.82E−03	9.23E−04
Coal, in ground	kg/MJ	1.27E−03	4.35E−02
Natural gas, in ground	m^3/MJ	3.04E−02	1.71E−04
Water	m^3/MJ	6.51E + 02	3.91E−05
Total land transformation	m^2/MJ	2.26E−05	1.19E−05
Total land occupation	m^2y/MJ	4.06E−04	8.46E−04

Table 6
Life cycle inventory data. Cofiring of coal combustion, coal/untreated biomass and coal/torrefied biomass. Functional unit 1 kWh electricity.

	Units	Coal	Coal/raw pellets	Coal/torrefied pellets
Atmospheric emissions				
CO_2 fossil	kg/kWh	2.66E + 00	2.24E + 00	2.38E + 00
CO_2 biogenic	kg/kWh	3.93E−02	2.43E−01	2.43E−01
N_2O	kg/kWh	6.32E−05	5.77E−05	5.97E−05
CO fossil	kg/kWh	1.99E−02	1.79E−02	1.86E−02
NO_x	kg/kWh	3.18E−02	2.83E−02	2.99E−02
SO_2	kg/kWh	1.41E−02	7.99E−03	7.69E−03
CH_4 fossil	kg/kWh	1.40E−03	1.22E−03	6.22E−03
CH_4 biogenic	kg/kWh	1.47E−05	1.29E−05	1.35E−05
PM 10	kg/kWh	8.27E−04	7.15E−04	7.34E−04
PM 2,5	kg/kWh	4.87E−04	4.26E−04	4.39E−04
NMVOC	kg/kWh	4.59E−04	4.31E−04	4.49E−04
Discharges to water				
BDO_5	kg/kWh	1.50E−03	1.43E−03	1.47E−03
COD	kg/kWh	1.68E−03	1.59E−03	1.64E−03
Sulfate	kg/kWh	1.54E−01	1.27E−01	1.29E−01
Nitrate	kg/kWh	1.13E−03	9.27E−04	9.45E−04
Phosphate	kg/kWh	5.98E−03	4.90E−03	5.00E−03
Natural resources				
Crude oil	kg/kWh	9.34E−02	9.29E−02	9.51E−02
Coal, in ground	kg/kWh	1.06E + 00	8.73E−01	8.90E−01
Natural gas, in ground	m^3/kWh	1.97E−01	1.72E−01	2.43E−01
Total water	m^3/kWh	1.54E + 06	1.39E + 06	1.43E + 06
Total land transformation	m^2/kWh	2.32E−03	2.04E−03	2.12E−03
Total land occupation	m^2y/kWh	1.91E−01	1.67E−01	1.72E−01

Table 7
CML characterized environmental impacts of coal and torrefied biomass. Functional unit 1 MJ.

Impact category	Unit	Coal	Torrefied wood
Abiotic depletion	kg Sb eq./MJ	$6.85\ 10^{-4}$	$6.09\ 10^{-4}$
Acidification	kg SO_2 eq./MJ	$1.22\ 10^{-4}$	$9.68\ 10^{-5}$
Eutrophication	kg PO_4 eq./MJ	$3.45\ 10^{-5}$	$1.42\ 10^{-4}$
Global warming (GWP100)	kg CO_2 eq./MJ	$1.17\ 10^{-1}$	$4.84\ 10^{-3}$
Ozone layer depletion (ODP)	kg CFC-11 eq./MJ	$2.48\ 10^{-9}$	$4.30\ 10^{-10}$
Human toxicity	kg 1,4-DCB eq./MJ	$1.15\ 10^{-2}$	$1.46\ 10^{-2}$
Fresh water aquatic ecotoxicity	kg 1,4-DCB eq./MJ	$1.84\ 10^{-1}$	$2.20\ 10^{-2}$
Marine aquatic ecotoxicity	kg 1,4-DCB eq./MJ	8.65	48.5
Terrestrial ecotoxicity	kg 1,4-DCB eq./MJ	$6.19\ 10^{-5}$	$2.11\ 10^{-5}$
Photochemical oxidation	kg C_2H_4 eq./MJ	$3.37\ 10^{-5}$	$2.64\ 10^{-6}$

be responsible for the lower global warming potential shown by torrefied pine. Indeed, at experimental conditions set here (viz. T = 280 °C, residence time = 30 min), about 75% of the energy required for torrefaction could be supplied by post-combustion of volatile compounds, hence an extra 25% should be met with other fuels. With that end, imported natural gas was used, and even so, results were very promising. Instead, if the extra heat is produced from biomass, this impact could be reduced to a minimum of 3% of that of coal.

Human toxicity, for coal was estimated at $1.15\ 10^{-2}$ kg 1,4-DCBeq./MJ, nearly 20% lower than for torrefied wood ($1.46\ 10^{-2}$ kg 1,4-DCBeq./MJ respectively). In the case of coal, this impact resulted mainly from the contribution of mining (84%) and in the case of biomass, came from both harvesting and transport (59%).

Fresh water aquatic ecotoxicity potential and Marine aquatic ecotoxicity, featured inverted patterns. In the case of coal production/transport life cycle, FAETP was equivalent to $1.84\ 10^{-2}$ kg 1,4-DCB-eq./MJ, which was around eight times higher than for torrefied biomass. Higher impact in FAETP for coal resulted from the extraction process (84%), particularly for the emissions of heavy metals such as Hg and Se. The picture for MAETP was similar, but showed a reduction of 83% for coal, mainly due to emissions related to the fertilization stage (see Fig. 6).

As shown in Fig. 6, transport accounted for the largest effect in *photochemical oxidation* for both fuels. The supply chain for coal involved long distance international shipping, hence a high effect of SO_2 emissions was expected. A similar pattern was reported by Tsalidis et al. (2014), who found that transport had been the main responsible for photochemical oxidation potential of solid fuels such as coal, pelletized biomass and torrefied biomass. In the case of torrefied wood, effects of

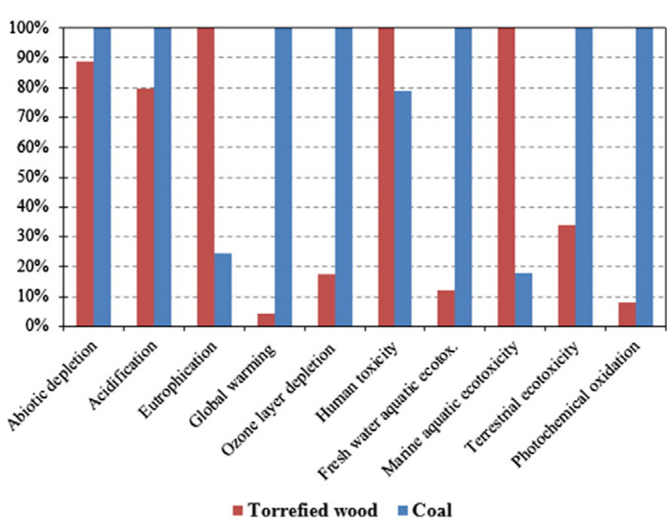

Fig. 5. Characterized results from the coal and torrefied biomass. CML 2 Baseline 2000 v2.05/World 1995.

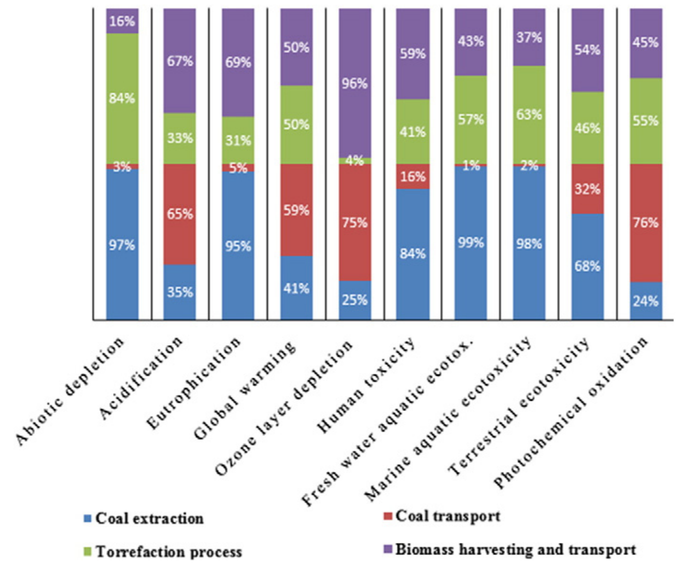

Fig. 6. Contribution of individual processes to total impacts. Coal vs torrefied biomass.

harvesting and torrefaction processes were proportionally similar (45 and 55% respectively). The first was associated to the NO_x release during harvesting (application of fertilizers) and the latter to the use of natural gas in the torrefaction plant.

Eutrophication potential of coal ($3.45\ 10^{-5}$ kg PO_4eq) was lower (76%) than for biomass. In the case of coal, this impact category was associated mainly to phosphate emissions during the mining stage (95% of total impact), while for biomass the main contribution can be attributed to the use of fertilizers during forestry processes (65%) (Atilgan and Azapagic, 2015). This finding agrees with previous reports such as of Cherubini et al. (2009), who reported that the use of crops residues in biorefinery processes could reduce GHG emissions but had higher eutrophication potential than fossil fuel systems. Moreover, Huang et al. (2013) found that the eutrophication potential of electricity production in Taiwan was 16 times higher for cofiring coal with biochar than that of coal fired plants. Nevertheless, these studies were based on the use of biomass coming from agricultural crops residues (rice, wheat).

Emissions of mercury, chromium, vanadium and arsenic to air and soil, are responsible for *terrestrial ecotoxicity potential (TEP)*. For coal, the TEP was $6.19\ 10^{-5}$ kg 1,4-DCB-eq./MJ, which was nearly three times that of torrefied biomass. Main stages affecting this category were the torrefaction process (46%) and biomass field operations (54%); while for coal, the mining stage accounted for 68% of this category.

The *ozone layer depletion (ODP)* for coal was estimated 83% higher than for torrefied wood. The 75% of ODP for coal, came from plant operations and transport. Major contributions of this category for torrefied wood come from field activities and emissions from transport of fuels and in particular halons 1211 and 1301 emissions used as fire suppressants and coolants in gas pipelines.

According to the previous discussion, torrefied wood (*P. radiata*) featured environmental advantages when compared to coal. Nevertheless, any feasibility analysis should carefully consider the design and processing during torrefaction. Most of the categories affected by the torrefaction process, resulted from the effect of using steam as torrefaction media and natural gas to produce such steam. Accordingly, further reduction of environmental impacts associated to torrefied biomass could be achieved by using pelletization processes and wood fuel instead natural gas. By pelletizing the torrefied material, the solid energy density increased up to 4 times as compared with untreated pellets, hence specific transport cost and impacts per MJ of energy contained in the fuel were reduced (Koppejan et al., 2012; Basu, 2013; Nhuchhen et al., 2014).

Table 8
Environmental profiles of the electricity production from: coal fired, coal/raw pellets and coal/torrefied pellets. Functional unit 1 kWh of electricity.

Impact category	Unit	Coal	Coal/raw pellets	Coal/torrefied pellets
Abiotic depletion	kg Sb eq./kWh	$2.00\ 10^{-2}$	$1.70\ 10^{-2}$	$1.86\ 10^{-2}$
Acidification	kg SO_2 eq./kWh	$3.32\ 10^{-2}$	$2.40\ 10^{-2}$	$2.45\ 10^{-2}$
Eutrophication	kg PO_4 eq./kWh	$1.03\ 10^{-2}$	$8.79\ 10^{-3}$	$9.10\ 10^{-3}$
Global warming (GWP100)	kg CO_2 eq./kWh	2.75	2.32	2.58
Ozone layer depletion (ODP)	kg CFC-11 eq./kWh	$4.41\ 10^{-8}$	$4.42\ 10^{-8}$	$4.52\ 10^{-8}$
Human toxicity	kg 1,4-DCB eq./kWh	3.86	3.20	3.27
Fresh water aquatic ecotoxicity	kg 1,4-DCB eq./kWh	2.26	1.88	2.33
Marine aquatic ecotoxicity	kg 1,4-DCB eq./kWh	$5.08\ 10^{3}$	$4.22\ 10^{3}$	$4.31\ 10^{3}$
Terrestrial ecotoxicity	kg 1,4-DCB eq./kWh	$2.13\ 10^{-2}$	$1.88\ 10^{-2}$	$1.94\ 10^{-2}$
Photochemical oxidation	kg C_2H_4 eq./kWh	$1.25\ 10^{-3}$	$9.03\ 10^{-4}$	$9.72\ 10^{-4}$

Impacts of cofiring untreated and torrefied biomass

Table 8 summarizes the environmental profiles of the studied cases, as defined in Goal and scope definition section. Impact categories included in this analysis were those that have been previously reported as critical for these processes (Benetto et al., 2004; Dias, 2013; Faé Gomes et al., 2013; Cambero and Sowlati, 2014; Tsalidis et al., 2014).

Fig. 7 compares the three alternatives, as percentage of impact points based on the CML baseline 2000.

As shown in Fig. 7, replacing 20% of coal with raw or torrefied wood pellets, for electricity production in coal fired plants, involved a reduction in most of the impact categories within CML 2. When compared to coal power, *ADP* for raw and torrefied pellets decreased by about 16% and 7% respectively. This is closely related to the renewability of biomass. In the case of torrefied pine, a small non-renewable charge should be added, due to the use of natural gas to fulfill the process energy requirements, hence its impact was higher. Moreover, using raw or torrefied pellets for cofiring, implied a slightly lower value for the PO_4eq than that obtained for coal combustion, yielding reductions in *EP* around 15% and 12% respectively. Combustion of coal would lead to higher emissions of gaseous NO_x, hence in spite torrefied biomass has higher *EP* than coal, its effect at 20% substitution rate was lower than that produced from NO_x emissions.

In Chile, global warming potential associated to electricity generation, is particularly important, since there is a declared commitment by the Chilean Government to attain significant reductions in the short term. According to the Carbon Dioxide Information Analysis Center (CDIAC — http://cdiac.ornl.gov/), the CO_2 emissions from carbon-fuel averaged 7.18 million tonnes CO_2/y in 2012. Thus, a GHG reduction as a result of biomass use in electricity generation is warmly welcome. Results from the LCA showed that a decrease the highest decrease (15.8%) was achieved when untreated pellets were cofired with coal, resulting in the lowest GWP among the studied cases. As known, global warming is caused due to the atmospheric accumulation of GHG, such as CO_2, N_2O and CH_4. Coal combustion releases fossil CO_2 to the atmosphere leading to a net accumulation of such GHG (Berc, 2014). On the other hand, the use of fuel biomass, does not lead to a net CO_2 accumulation in the atmosphere, as it is part of the photosynthesis closed loop (Berc, 2014). In the case of torrefied pellets, CO_2 emissions were also reduced to 4990 kg CO_2/kg-fossil and 1426 kg CO_2/kg renewable as compared with coal combustion. This was estimated on the basis of experimental values from the torrefaction pilot plant and considering 80% less electric energy consumption in biomass grinding (Phanphanich and Mani, 2011; Batidzirai et al., 2013). These results would suggest that biomass could linearly substitute coal from its actual applications, leading to a direct reduction on the GWP of the technology. However, the real situation might be more complex. In some cases (especially older installations with lower efficiencies) there would be greater flexibility to replacing coal with biomass. Modern, efficient installations, however, would allow only smaller amounts of biomass (usually 10–20%) without changing greatly the characteristics of the entire system. The latter would be mainly due to the tight specification of the feeding systems (especially in pulverized boilers).

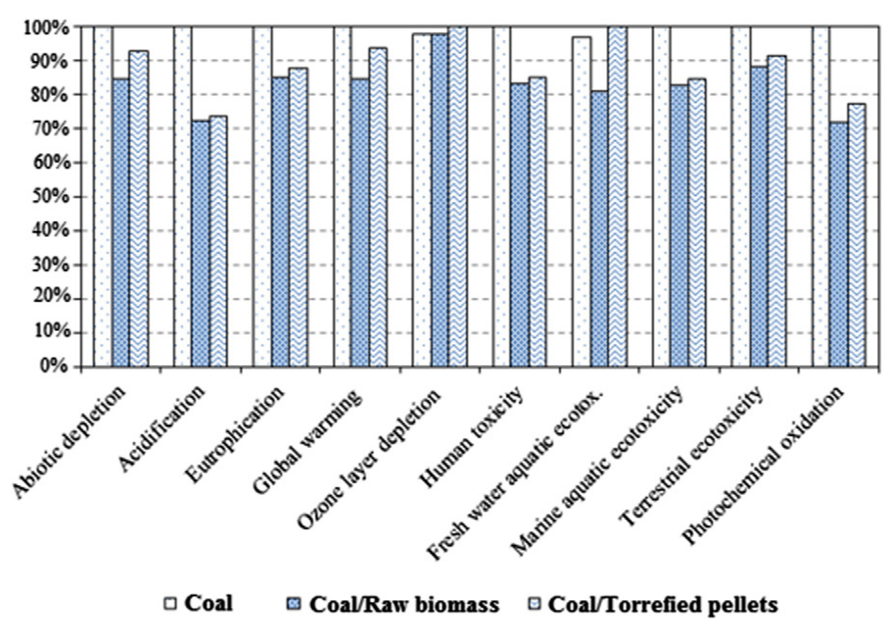

Fig. 7. Characterized results on environmental impacts from the cofiring and combustion. CML 2 Baseline 2000 v2.05/World 1995.

As biomass contains negligible amounts of sulfur, it is expected that low SO_2 emissions would be expected during combustion. Thus, higher substitution of coal by biomass should linearly reduce SO_2 emissions and its effect on the acidification as shown in Fig. 7. Furthermore, *HTP*, *TETP* and *MAETP* impact categories were also improved when biomass was used as coal substitute. Reductions in these categories ranged from 9 to 17%, which was similar to other literature reports (Schakel et al., 2014; Atilgan and Azapagic, 2015). A quite interesting result was found for *FAETP*, which was slightly higher (3%) for cofiring coal with torrefied pellets. This fact would be related to the torrefaction media used as reference here (steam) and to the fuel considered to produce this steam (natural gas). The majority of the impact for coal was due to metals emissions to fresh water during mining, including nickel, beryllium, cobalt, vanadium, copper and barium. Finally, *photochemical oxidation potential* was reduced by 28 and 23.4% respectively, for raw and torrefied pine.

Conclusions

In this paper, Life Cycle Inventory and Impact Assessment were used to compare the environmental profiles of imported coal to that of raw and torrefied wood pellets, in electricity generation. Results demonstrated that cofiring coal with biomass is a very attractive alternative to reduce environmental impacts associated to electricity generation in Chile. Indeed, this study shows that cofiring coal with raw or torrefied wood pellets may lead to important reductions in impact categories such as, AP (28–26%), ADP (15–7%), EP (15–12%), GWP (16–6%), POP (28–23%), HTP (17–15%), TETP (12–9%), and MAETP (17–15%). The use of non-renewables for carrying out torrefaction – using steam as heating media – implies that categories FAETP and ODP for torrefied wood pellets were similar to that of coal. Therefore, it is very important to integrate process synthesis with environmental assessment tools, to determine to which extent the sustainability of existing coal-fired plants could be improved. These findings constitute a significant contribution to the new regulations that Chilean government is implementing in order to reduce the environmental impacts of coal-based electricity generation in the country.

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